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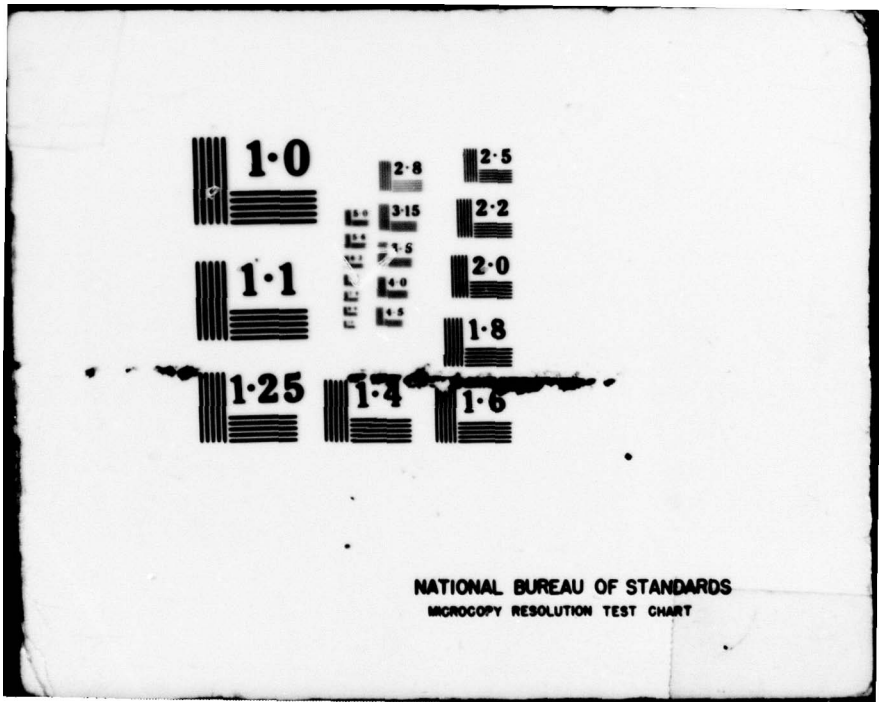
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FUNDAMENTAL CONCEPTS IN DISCRETE OPTIMIZATION AS RELATED TO CLASSES OF SCHEDULING PROBLEMS

Final Report

Salah E. Elmaghraby
Principal Investigator

November 10, 1978

U. S. Army Research Office

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This is the final report on research activities that spanned the period between mid-1972 to mid-1978. It gives the personnel involved in the research during those 6 years, professional activities undertaken (mostly attending conferences) and the research reports and published papers that were partially supported by the grants.

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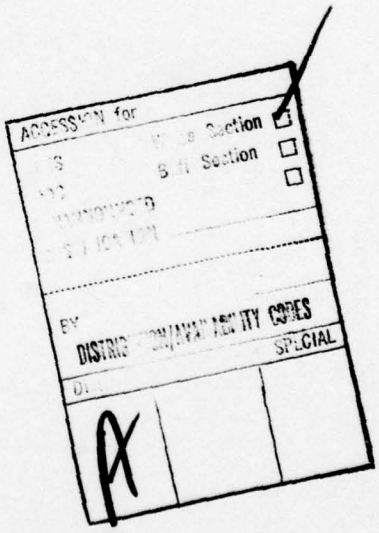
FOREWORD

This is the final report on research grants DA-ARO-D-31-124-72-G106, DAHC04-75-G-0181, and DAAG29-79-G-0204, which spanned the period from mid-1972 to mid-1978.

Activities during the first three years are briefly summarized herein - a more detailed exposition of accomplishments and research findings during those years may be found in our request for renewal submitted on December 11, 1974. Research findings during the last three years are presented in more detail.



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SUMMARY OF ACTIVITIES IN THE YEARS 1972-75

Abstract of Research Findings

Work accomplished over the first three years (1972-75) under Contract No. DA-ARO-D-31-124-72-G106 may be summarized as follows:

(1) An extensive study of models for optimally scheduling lots of N products on a single processor under various demand process structures.

(2) Solution of a problem of scheduling N jobs on parallel processors to minimize a penalty function based on job due dates when there are no precedence relations among jobs.

(3) Two studies treating the efficient solution of minimum cost flow problems.

(4) Research on methodologies for discrete optimization related to

(a) Tree search in methods of implicit enumeration,

(b) Circumventing the "curse of dimensionality" in dynamic programming,

and (c) The reduction method of integer programming for a specialized version of the generalized assignment problem.

(5) Surveys of past and current research in

(a) Scheduling multiple processors,

(b) Flow networks,

(c) Project planning networks,

(d) Basic concepts used in branch-and-bound,

and (e) Production planning.

In addition several other studies were initiated with the expectation of completion during the proposed renewal period.

Personnel (1972-75)

The personnel involved in the research varied over the years 1972-75. The principal investigator (S. E. Elmaghraby) remained unchanged throughout, but the associate investigators and research assistants have varied. Drs. Gerald E. Bennington and Henry L.W. Nuttle were associate investigators (ONR) during the first year. During 1972-73 Dr. Nuttle was on leave, while Dr. Bennington continued until leaving the University in July, 1973. The research assistants during this period were:

Mr. Jerry Allen - Master's candiate
Mr. A. A. Elimam - Doctoral candidate
Mr. S. Sarin - Doctoral candidate
Ms. Lynn P. Dix - Master's candidate
Mr. S. Park - Master's candidate
Mr. R. Coppins - Doctoral candidate

While these students received direct support from the grants, others became involved in the research effort through the principal and associate investigators' acting as their research advisors. The students' research interests were stimulated by this research, and channelled into this direction. Thus, while not receiving direct support from the grants, they contributed to it and their work figured prominently in the research.

Mr. Worley - Master's candidate (under Elmaghraby)
Mr. Dodin - Master's candidate (under Elmaghraby)
Mr. Wu - Master's candidate (under Nuttle)
Mr. Aly - Master's candidate (under Nuttle)
Mr. Arisawa - Doctoral candidate (under Elmaghraby)
Mr. McGinnis - Master's candidate (under Bennington)

The research also benefitted from the valuable contribution of Dr. A.N. Elshafei, visiting Assistant Professor in Operations Research at NCSU, who

spent the Spring Semester of 1974 with us. Dr. Elshafei co-authored two reports with Elmaghraby on scheduling.

Relevant Conferences Attended

In conjunction with the research effort, the investigators attended and participated in the following conferences.

Conference	Location	Date	Attendee
Symposium on Scheduling Theory and Its Application	NCSU	May 15-17, 1972	Elmaghraby Nuttle
Systems Conference, AIIE	New York City	Nov. 29, 1973	Elmaghraby
National Meeting, AIIE	Chicago	May 23-24, 1973	Elmaghraby
National Meeting, ORSA	San Diego	Nov. 12-14, 1973	Elmaghraby
National Meeting, ORSA/TIMS	Boston	April 22-24, 1974	Nuttle
Logistics Research Conference	Wash., DC	May 8-10, 1974	Elmaghraby Nuttle
National Meeting, AIIE	New Orleans	May 21-24, 1974	Elmaghraby
U.S. National Committee for Building Research	Wash., DC	July 17, 1974	Elmaghraby
National Meeting, ORSA/TIMS	San Juan	Oct. 16-18, 1974	Nuttle

ACTIVITIES IN YEARS 1975-78

Personnel

This research was initiated in mid-June 1975 as a continuation of research that came to end in mid-May 1975. It officially ends mid-June 1978, but no cost extension was granted through mid-August 1978.

The principal investigator (S. E. Elmaghraby) and the associate investigator (Henry L. W. Nuttle) remained unchanged throughout, but graduate research assistants did change, with a good number of them employed for a brief period (say part or all of the summer months) to perform specific assignments (mostly to program algorithms on the computer). Among those students partially supported are:

Mr. A. A. Elimam - Doctoral candidate (Graduated)

Mr. Subhash Sarin - Doctoral candidate (Graduated)

Ms. Eleanor Walther - Doctoral candidate

Ms. Hanan Samara - Masters candidate

Ms. Simin Pulat - Doctoral candidate

Mr. E. Abdel-Gawad - Masters candidate

Relevant Professional Activities

In conjunction with the research effort, the principal and associate investigators have participated in the following conferences.

S. E. Elmaghraby

Date	Conference	Function(s)
Nov. 17-19, 1975	ORSA/TIMS Meeting; Las Vegas, Nevada	Chaired a session on "Production Systems". Presented a paper, "Sequencing Jobs on a Single Machine to Minimize Total Weighted Tardiness When All Jobs Have the Same Due Date".
Feb. 4-6, 1976	ORSA/TIMS Special Interest Conference on the Theory and Applications of Scheduling; Orlando, Fla.	Chaired a session and presented a paper, "On Scheduling n products on a single facility under constant demands and production rates".
March 4, 1976	Univ. of Minnesota Dept. of Mech. Engr.	Invited lecture: The n-product single machine problem under constant demand and production rates.
July 26-30, 1976	JACC, Purdue Univ.	Invited talk: Recent developments in scheduling theory.
Sept. 14-16, 1976	Fifth Conf. on Algorithms for Production Control & Scheduling; Karlovy Vary, Czechoslovakia	Presented paper, "The EMQ Revisited: New Wine in Old Bottles".
Aug. 22-28, 1977	Fourth International Conf. on Production Research; Tokyo, Japan	Chaired a session and presented an invited paper, "An extended basic period approach to the ELSP".

Date	Conference	Function(s)
Nov. 7-9, 1977	ORSA/TIMS Meeting; Atlanta, Georgia	Chaired a session on Production Systems, and presented a paper, "Optimal project compression with due-dated events".
May 8-11, 1978	International Conf. on Systems Modelling; Bangkok, Thailand	Chaired a session and presented a paper, "Activity Networks: Their Uses & Misuses in Project Planning and Control".
Henry L. W. Nuttle		
May 20-23, 1975	AIIE Meeting; Washington, D. C.	Attended Meeting
Nov. 17-19, 1975	ORSA/TIMS Meeting; Las Vegas, Nevada	Presented paper, "Sequencing jobs on a single machine to minimize total weighted tardiness when all jobs have the same due date".
Feb. 4-6, 1976	ORSA/TIMS Special Interest Conf. on the Theory & Applications of Scheduling; Orlando, Fla.	Attended Meeting
Nov. 3-5, 1976	ORSA/TIMS Meeting; Miami, Fla.	Chaired a session on Scheduling.
May 1-3, 1978	ORSA/TIMS Meeting; New York City	Chaired two sessions on Scheduling and presented a paper, "Sequencing jobs with a single resource".

Research Findings

In the Proposal of 1975 we stated that our research has two facets: short-term and long-term. We briefly enumerate the stated objectives and delineate their degree of accomplishment.

A. Short-Term Research

1. To report on the Hub-and-Wheel Scheduling Problem.

This was accomplished in OR Report Nos. 102 and 106. It was then submitted for publication in Transportation Science and was accepted. Two papers appeared in Vol. 11, No. 2, pp. 124-146 and 147-165, May, 1977.

2. To report, in a unified and cohesive manner, on the various results obtained individually on the generalization of the classical EMQ model.

This is partially accomplished but is not completed due to our discovery of other "gaps" in the current "state of the art". We are constantly diverted to do research and/or further elaboration, leaving the task of stock-taking unfinished (see Long-Term Research below).

3. To report on the approximation methods in dynamic programming.

This task was completed but never reported in a formal way because of the more recent developments in the theory of approximation in DP (especially the work of van Nunen, Wessels and Whitt) that superseded our work and left it in need of updating.

4. To report on the multi-product, single processor problem with end-of-horizon demand and sequence-dependent changeover costs.

Extensive computing experience with the programs developed for this purpose revealed excessive computing requirements (the problem combines Knapsack and Traveling Salesman features), and work was halted on this phase of research by Nuttle.

5. To finalize work on the problem of single processor scheduling when all jobs have the same due date but varying penalties for tardiness.

This work has just been completed (June 1978) and a report on it is in preparation based on the Master's theses of J. Allen, B. J. York, and P. Woolfolk, III, all working with Nuttle.

6. To continue work on the model for minimizing the "makespan" for n jobs on m-machines.

This work was continued with considerable success (see Long-Term Research below).

7. To continue the study of project planning under scarce resources when both activity start times and activity durations are control variables.

An extensive survey of literature revealed serious misconceptions in the application of heuristic methods to project planning under limited resources. We undertook a fundamental study of the problem, which is discussed in more detail under "Long-Term Research" below.

8. To continue a program of "familiarization" with the maintenance problem at Air Force bases.

Three visits to Seymour Johnson Air Force Base in N. C. were made, but the effort was discontinued due to change in personnel in the AF contact office that spurred the initiative.

B. Long-Term Research

The main thrust of the research was directed towards three problems:

1. Scheduling independent tasks on multiple processors.
2. Scheduling precedence-related tasks, with or without resource constraints.
3. Scheduling of the so-called "economic lots" on a single facility.

We elaborate on each thrust of research.

1. Scheduling Independent Tasks on Multiple Processors

As was previously indicated in the Proposal of 1975 (see pages 18-20), the problem gives rise to a generalized assignment (GA) model of the form:

minimize z,

subject to:

$$\text{Schedule constraints} \quad \sum_j p_j x_{ij} - z \leq 0; \quad \text{all } i$$

$$\text{realization constraints} \quad \sum_i x_{ij} = 1; \quad \text{all } j$$

$$x_{ij} = 0,1 \text{ and } z \text{ integer} > 0$$

in which $x_{ij} = 1$ if task j is scheduled on machine i; and is = 0 otherwise; p_j is the processing time of task j, and z represents the makespan.

We attacked this problem via three approaches:

(a) Specialized Reduction. The very special structure of the 0,1 integer model of GA invites specialization of the reduction method (RM), especially as applied to the "schedule constraints". This reduction takes into account implicitly the generalized

upper bound constraints of the form $\sum_j x_{ij} = 1$. The objective of this extension of the RM is to generate as small coefficients as possible in the final reduced equation.

The results of this research were reported in OR Report No. 125, "On the reduction method for integer linear programs", March 1978, by S. E. Elmaghraby and A. A. Elimam. This report has been submitted for publication in Oper. Res.

(b) Knapsack-Based Heuristics. These are based on the elementary observation that scheduling on two machines is easily reduced to a Knapsack problem. We devised an iterative heuristic procedure that capitalizes on this observation. Extensive computational experience indicates the superiority of this approach over other existing approaches. Realistic problems of up to 100 jobs on 10 machines are solved in less than one second. This research is reported in OR Report No. 124, "Knapsack-based approaches to the makespan problem on multiple processors", April 1978, by S. E. Elmaghraby and A. A. Elimam; submitted for publication to the IE Transactions.

(c) Branch-and-Bound. The problem GA is known to be NP-complete, hence there is ample justification to resort to schemes of implicit enumeration. The thrust of this research was to develop the best search and elimination procedures that capitalize on the very special structure of the problem.

The results of this research are in typing and will appear as OR Report No. 137, "The makespan problem on multiple processors: A Branch-and-Bound approach", by S. E. Elmaghraby and A. A. Elimam.

2. Scheduling Precedence-Related Tasks

The problem with arbitrary precedence is known to be NP-complete, even when restricted to unit tasks (i.e., tasks that consume one unit of time to process). This fact led us to follow two paths of investigation in this problem: the first is to define the most general class of precedence for which a polynomial order algorithm is obtainable; and the second is to seek "reasonable" heuristics and develop bounds on their worst-case performance.

(a) Relative to the first objective, we have developed an algorithm that is applicable to the scheduling of tasks whose precedence is of the transitive series-parallel class. We believe that this is the most general class for which a polynomial-bounded algorithm is applicable. A report on this algorithm is in preparation.

(b) Relative to the second objective, we have proposed a heuristic that presupposes the availability of an optimal schedule on a single machine. The procedure would simply assign tasks in the order of their appearance in the 1-machine optimal schedule to the m-machines, while respecting precedence. We demonstrate that the performance of this heuristic is bound by m/α, where $\alpha > 1$ and m is the number of machines. For $m = 2$ (the case of two machines) this bound is "tight", in the sense that it is realizable, hence it is the strongest possible.

This work has been reported in OR Report No. 117, "On scheduling precedence-related jobs on parallel machines: Bounds on the performance of a heuristic", Nov. 1977, by S. E. Elmaghraby

and Subhash Sarin. It has been submitted for publication to Management Science.

(c) Studies in the area of scheduling precedence-related tasks lead in a natural way to studies in activity networks (ANs). We had previously reported that a manuscript on the subject was in preparation by S. E. Elmaghraby. We are pleased to report the completion of the manuscript and its publication as a hard-bound book by Wiley-Interscience in early 1978. The support of the ARO is gratefully acknowledged in the Preface of that book.

(d) An important problem in the field of ANs is that of optimal project "compression". This problem was treated as early as 1961 by Fulkerson, who dealt with a single terminal event. We generalized his work to an arbitrary number of "key events" that are due-dated and the project is penalized if they are realized after their due dates. A primal-dual algorithm based on flow interpretation was developed. It is reported in OR Report No. 116, "Optimal project compression with due-dated events", July 1977, by S. E. Elmaghraby and P. Simin Pulat. It was submitted for publication to Nav. Res. Log. Quart. and was accepted. The report is currently being revised with minor modifications, and hopefully will appear in 1979.

(e) The scheduling of activities under constraints of limited resource availabilities is evidently NP-complete, and heuristics abound for its resolution. Unfortunately, it has not been possible to conduct any comparative analysis of the proposed heuristics mainly

due to the lack of a "measure of network complexity". Worse still, a survey of the literature on this problem revealed to us startling inconsistencies and invalid deductions, which led us to take a fundamental look at the theory of measurement and its application to the problem in hand. The fruits of our research have been reported in OR Report No. 121, "On the measurement of complexity in Activity Networks", Dec. 1977, by S. E. Elmaghraby and Willy Herroelen. The report was submitted for publication to Networks. However, our continued work on the problem has yielded new results which, combined with the referee's reaction, have caused us to undertake a major revision of the manuscript. Such revision is currently underway.

(f) The "state-of-the-art" and some outstanding problems in the theory of ANs were reported in OR Report No. 123, "Activity Networks: Their uses and misuses in project planning and control", Jan. 1978, by S. E. Elmaghraby. The paper appeared as Chapter 4 in Systems Models for Decision Making, edited by N. Sharif and P. Adulbhan, The Asian Institute of Technology, May 1978.

(g) The problem of sequencing n jobs for processing by a single resource with varying availability over time was studied. The approach was to investigate the extent to which a number of well-known sequencing rules for single machine (constant resource) problems can be applied with little or no modification to the corresponding variable resource problems to produce optimal sequences, where optimality is relative to minimizing a function

of job completion times. With one notable exception, namely, the minimization of weighted completion times, it was found that the single machine decision rules apply intact to the generalized problem as well. This research is summarized in OR Report No. 133, "Sequencing jobs with a single resource", May 1978, by H. L. W. Nuttle and Kenneth R. Baker.

3. Scheduling of Production on a Single Facility

It was stated in our Proposal of 1975 that a natural extension of our research to date is in the direction of unbounded planning horizon. The link between that problem and the classical economic manufacturing quantity, (EMQ), is self-evident and needs no elaboration.

Our first step was to conduct a comprehensive review of contributions to the problem, identify their limitations and, if possible, to extend the results available thus far. This was accomplished and reported in OR Report No. 112, "The economic lot scheduling problem (ELSP): Review and extensions", Aug. 1976, by S. E. Elmaghraby. The paper was submitted for publication and subsequently appeared in Management Science, Vol. 24, No. 6, 1978, pp. 587-598.

A separate report that details a dynamic programming model briefly mentioned in the above paper is OR Report No. 115, "An extended basic period approach to the economic lot scheduling problem #LSP)", July 1977, by S. E. Elmaghraby. This manuscript appeared in the Proceedings of the 4th International Conference on Production Research, held in Tokyo, Japan, August 22-28, 1977.

After that initial step it became evident that the ELSP is an elementary concept that loses its validity in many production systems due to the effects of "learning" and "forgetting". In other words, the classical ELSP presumes constant rate of production, which need not be the case: the rate may be dependent on the very size of the lot and on the number and/or duration of the interruption between successive lots. This aspect of scheduling lots has never been investigated before, to the best of our knowledge. A good part of our current research is devoted to this problem (see Proposed Research below).

C. Summary

To sum up, our research has resulted in the following reports:

Report No.	Date	Author(s)	Title & Remarks
102	March 1975	S. E. Elmaghraby Sanji Arisawa	"The 'Hub' & 'Wheel' Scheduling Problems, Part I: The 'Hub' Scheduling Problem (HOSP): The Myopic Case". Appeared in Trans. Sci., 11(2), 1977, 124-146.
106	Oct. 1975	S. E. Elmaghraby Sanji Arisawa	"The 'Hub' & 'Wheel' Scheduling Problems, Part II HOSP: Multi-Period & Infinite Horizon, and The Wheel Operation Scheduling Problem (WOSP)". Appeared in Trans. Sci., 11(2), 1977, 147-165.
112	Aug. 1976	S. E. Elmaghraby	"The Economic Lot Scheduling Problem (ELSP): Review and Extensions". Appeared in Mgt. Sci., 24(6), 1978, 587-598.
115	July 1977	S. E. Elmaghraby	"An Extended Basic Period Approach to the Economic Lot Scheduling Problem (ELSP)". Appeared in Proc. 4th ICPR, Tokyo, Japan, Aug. 22-30, 1977.

Report No.	Date	Author(s)	Title & Remarks
116	July 1977	S. E. Elmaghraby P. Simin Pulat	"Optimal Project Compression with Due-Dated Events". Accepted for publication, Nav. Res. Log. Quart.
117	Nov. 1977	S. E. Elmaghraby Subhash Sarin	"On Scheduling Precedence-Related Jobs on Parallel Machines: Bounds on the Performance of a Heuristic". Submitted for publication, Mgt. Sci.
121	Dec. 1977	S. E. Elmaghraby Willy Herroelen	"On the Measurement of Complexity in Activity Networks". Under revision to incorporate new results.
123	Jan. 1978	S. E. Elmaghraby	"Activity Networks: Their Uses and Misuses in Project Planning and Control". Appeared as Chapter 4 in Systems Models for Decision Making, Asian Inst. of Tech., May 1978.
124	April 1978	S. E. Elmaghraby A. A. Elimam	"Knapsack-Based Approaches to the Makespan Problem on Multiple Processors". Submitted for publication, IE Trans.
125	March 1978	S. E. Elmaghraby A. A. Elimam	"On the Reduction Method for Integer Linear Programs". Submitted for publication, Oper. Res.
133	May 1978	H. L. W. Nuttle Kenneth R. Baker	"Sequencing Jobs with a Single Resource". Presented at the Joint ORSA/TIMS Meeting, New York City, May 1-3, 1978.
137	Sept. 1978	S. E. Elmaghraby A. A. Elimam	"The Makespan Problem on Multiple Processors: A Branch-and-Bound Approach". To be submitted for publication, Nav. Res. Log. Quart.
Book	Dec., 1977	S. E. Elmaghraby	Activity Networks: Project Planning and Control by Network Models, Wiley-Interscience, 444 pp. + xvii

Biographical Data

(Salah E. Elmaghraby)

Currently University Professor of Operations Research and Industrial Engineering, and Director, Graduate Program in Operations Research, at North Carolina State University at Raleigh. Prior to joining N. C. State University, Dr. Elmaghraby was Associate Professor in the Department of Administrative Sciences at Yale University (1962-1967), and prior to that, research leader at the Western Electric Engineering Research Center, Princeton, N. J. (1958-1962). He earned his baccalaureate degree in Mechanical Engineering from Cairo University, his M.Sc. from Ohio State University and his Ph.D. from Cornell University.

Dr. Elmaghraby has published four books, three as authors, including the recent Activity Networks, Wiley (publisher), and one as Editor. He has over forty papers to his credit in scientific journals and proceedings of symposia, and is Co-Editor of the Handbook of Operations Research, Van Nostrand-Reinhold (publisher).

Dr. Elmaghraby is widely traveled and is active in the professional societies. He is currently Departmental Editor of the IE Transactions for the area of Production Planning and Scheduling. He was the recipient of the AIIE distinguished research award, 1970.

Biographical Data

(Henry L.W. Nuttle)

Currently Associate Professor of Industrial Engineering at North Carolina State University at Raleigh. Dr. Nuttle joined North Carolina State University in 1966. He has a B.Sc. degree in Mathematics from Dickinson College and a Ph.D. in Operations Research from Johns Hopkins University.

Dr. Nuttle is the author of six papers published in scientific journals and proceedings of symposiums, plus a number of technical reports and papers delivered at professional society meetings.

He is a member of the American Institute of Industrial Engineers, Operations Research Society of America, and The Institute of Management Science. He also serves as referee for the Journals of these societies.